Subarcsecond imaging of 3C 273 at 150 MHz

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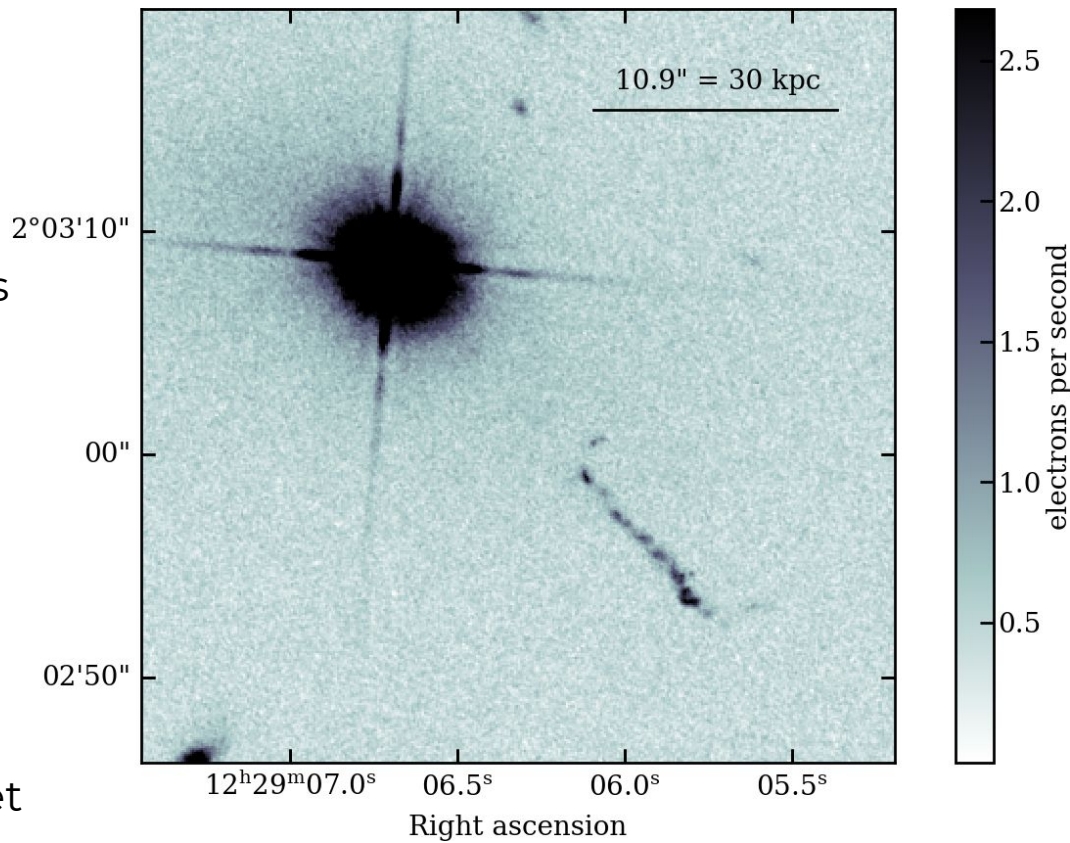
Context

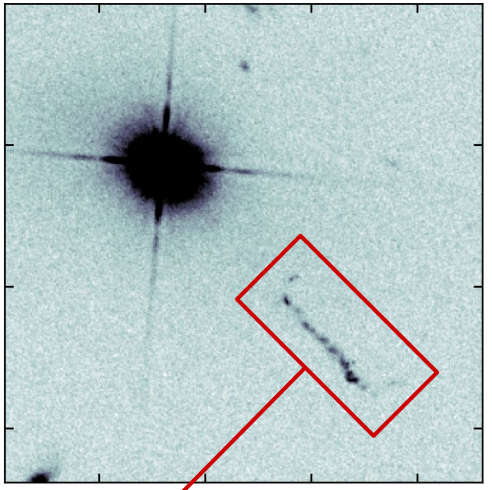
- 1st identified quasar
- z = 0.158
- Emission mechanism of X-ray knots not well-understood
- Counterjet not detected
- Low-frequency spectrum relatively unexplored
- $\lesssim$ 1” resolution required to resolve jet

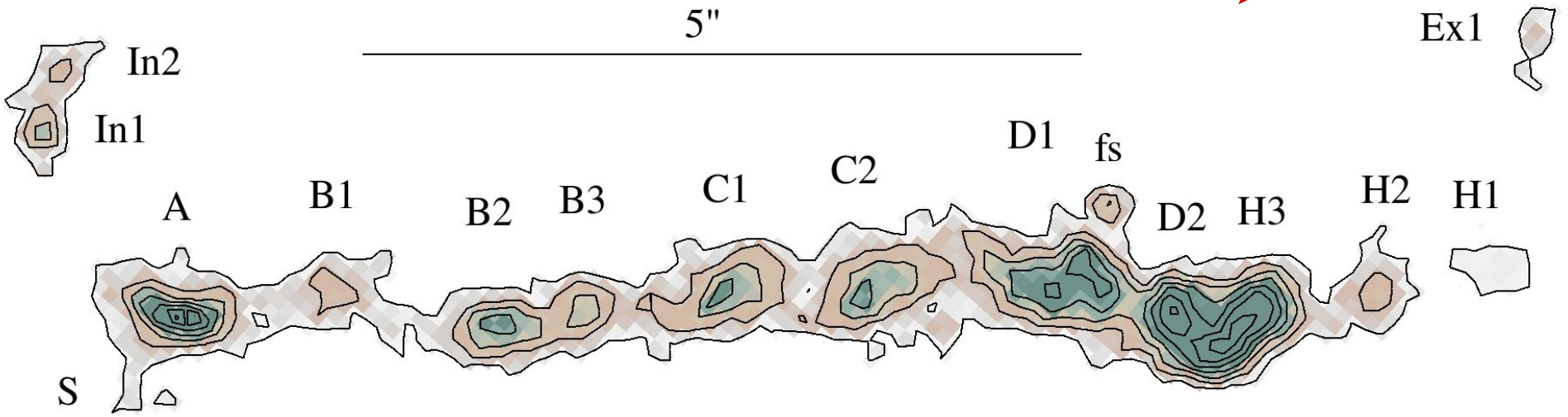
HST image



Feature nomenclature

- Naming convention from Jester et al. (2007)
- In1, In2, Ex1, fs, and S are unrelated galaxies or stars





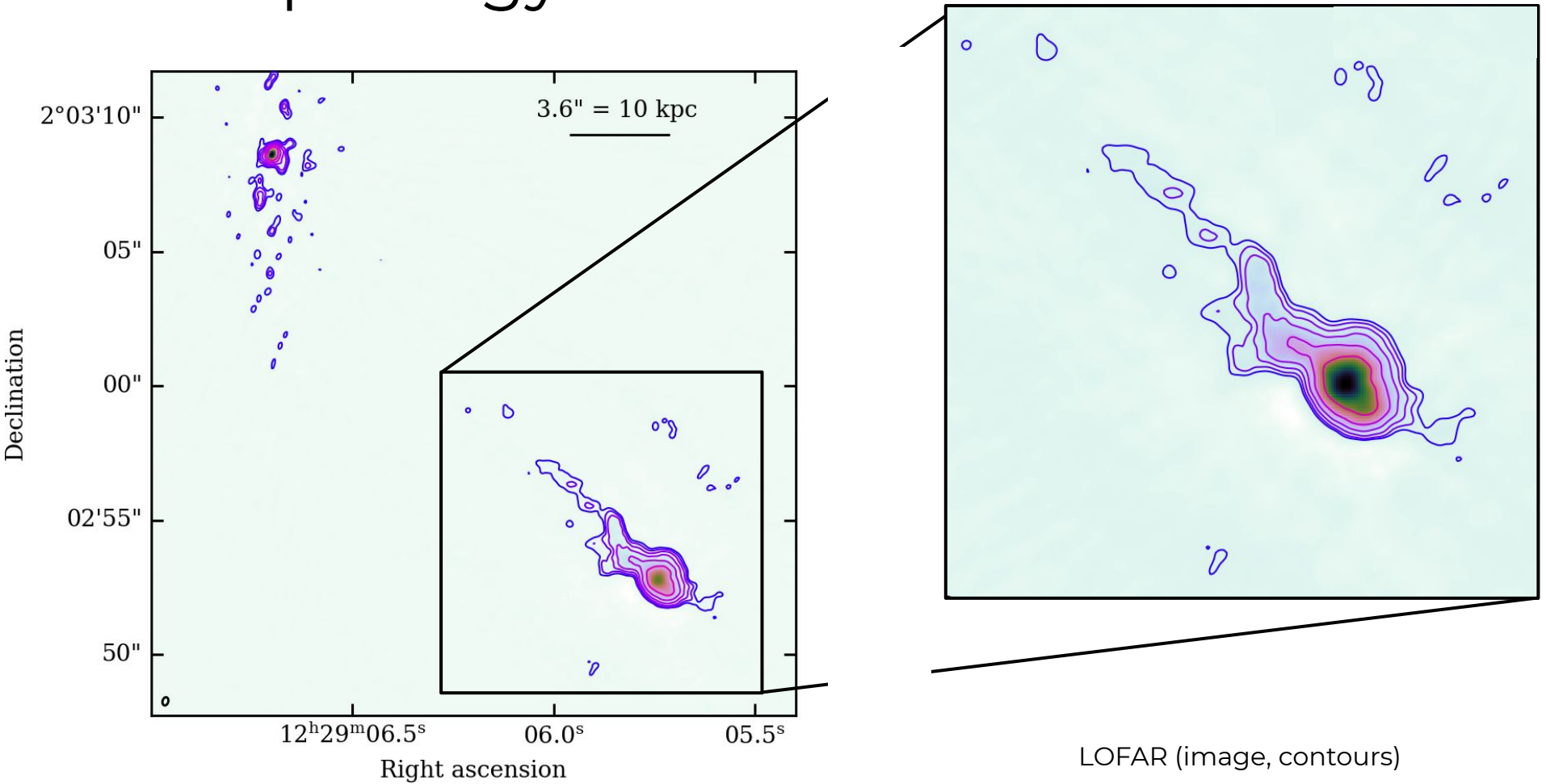
Aims

1. Resolve the jet at 150 MHz
2. Measure the diffuse emission
3. Detect or set an upper-limit on the flux of a possible counterjet

Analysis

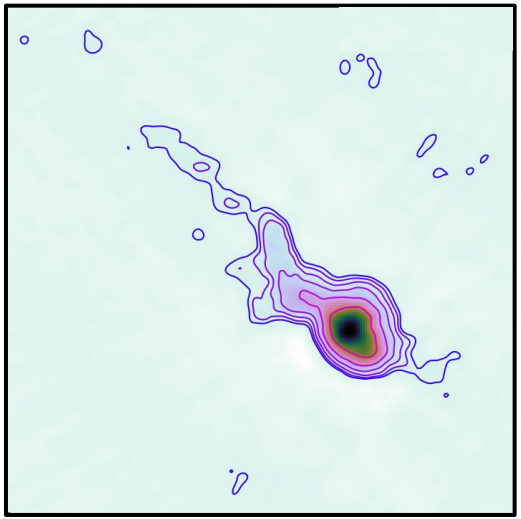
- Took 12h HBA and 12h LBA data in 4h observations (LC7_017, LC8_032)
- Presenting best HBA observation here
- Steps (carried out in the Singularity image):
    a. Prefactor (international baselines included; 3C 295 model courtesy of Frits)
    b. Long-baseline pipeline
    c. Self-calibration
- Initial model of 3C 273 provided by Christian

Jet morphology at 150 MHz

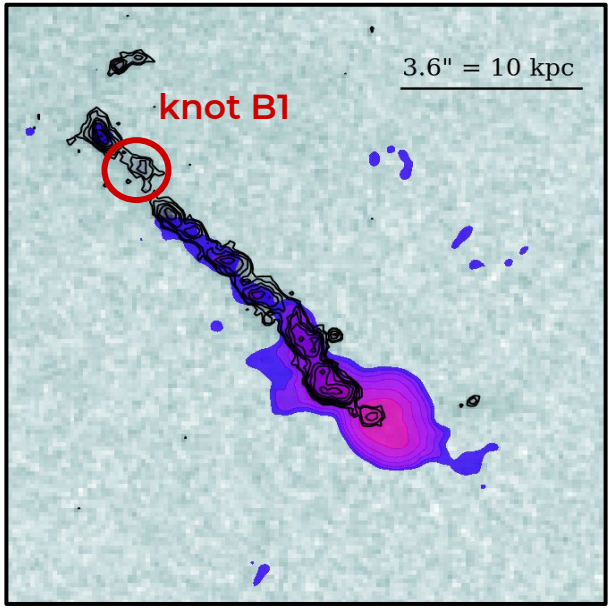


LOFAR (image, contours)

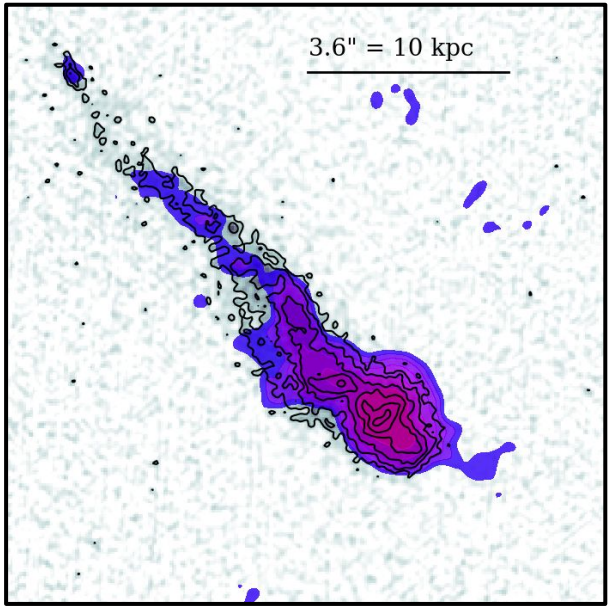
LOFAR compared with *HST* and VLA



LOFAR (image, contours)



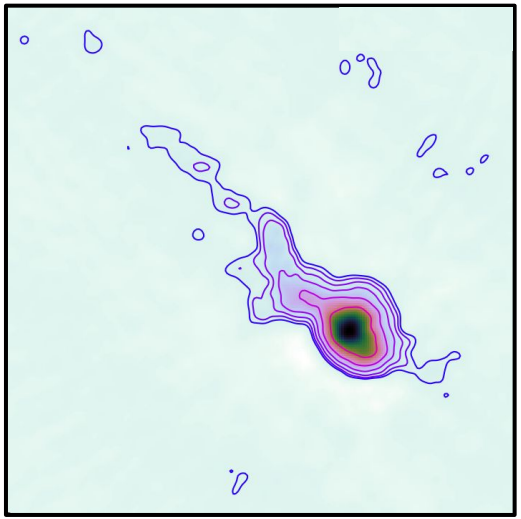
HST (image, contours),
LOFAR (filled contours)



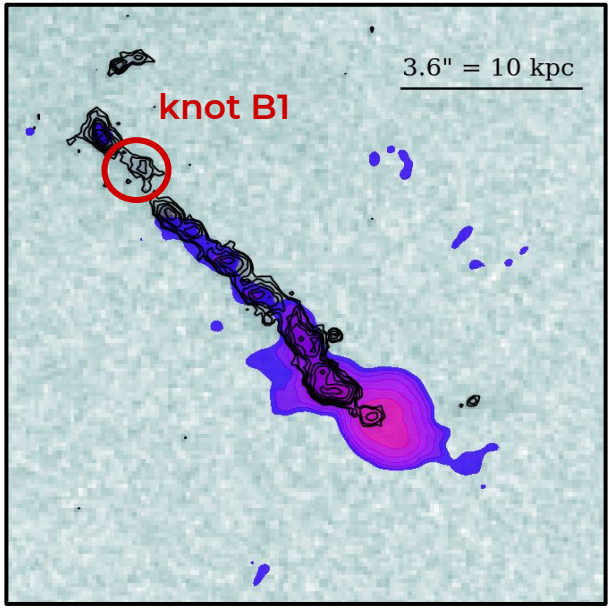
VLA 15 GHz (image, contours),
LOFAR (filled contours)

Perley & Meisenheimer (2017)

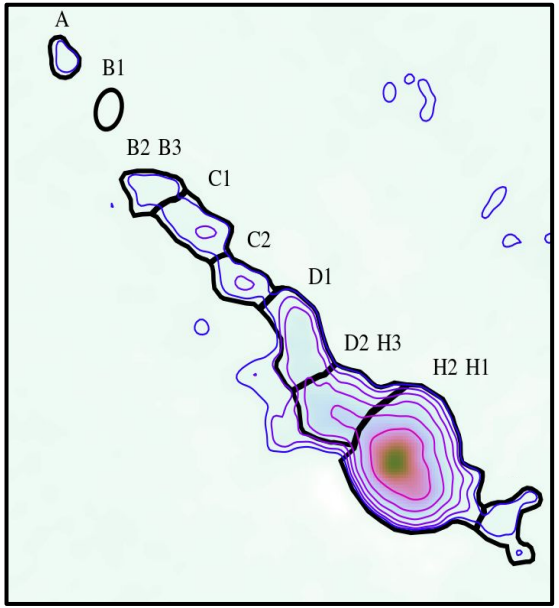
Extract knots from LOFAR image



LOFAR (image, contours)



HST (image, contours),
LOFAR (filled contours)

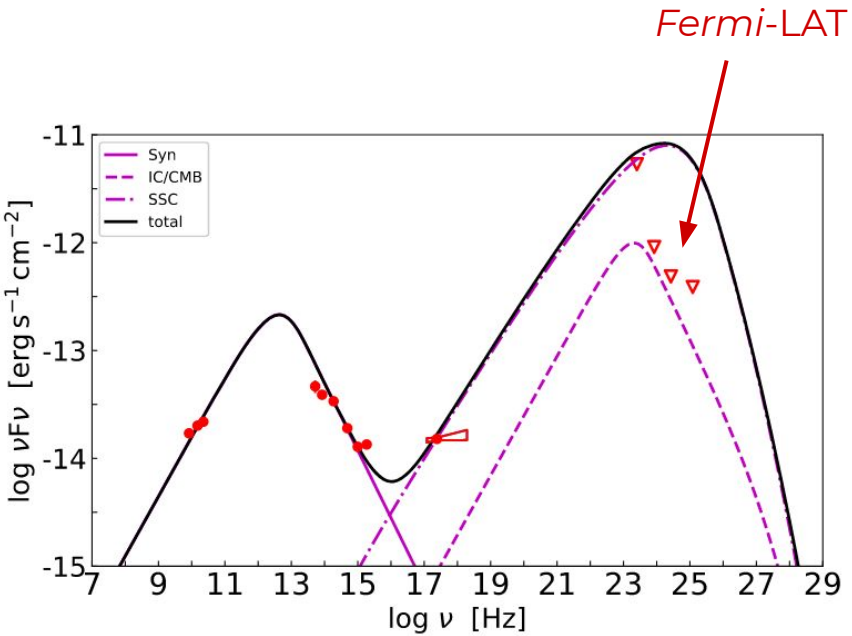


LOFAR image with knots marked

Knot SEDs

Explaining the X-ray emission via IC/CMB & SSC has been effectively ruled out by, among other arguments:

- Proper motion studies suggest low relativistic bulk speeds ($\Gamma < 2.9$; Meyer+ 17)
- γ-ray flux predictions from IC/CMB & SSC models exceed observational upper limits from *Fermi*-LAT (Meyer+ 15)



e.g. knot C2 from Wang+ 20

Prevailing theory is X-ray emission is synchrotron from a 2nd population of particles

Can LOFAR be useful modeling this scenario?

Knot SEDs

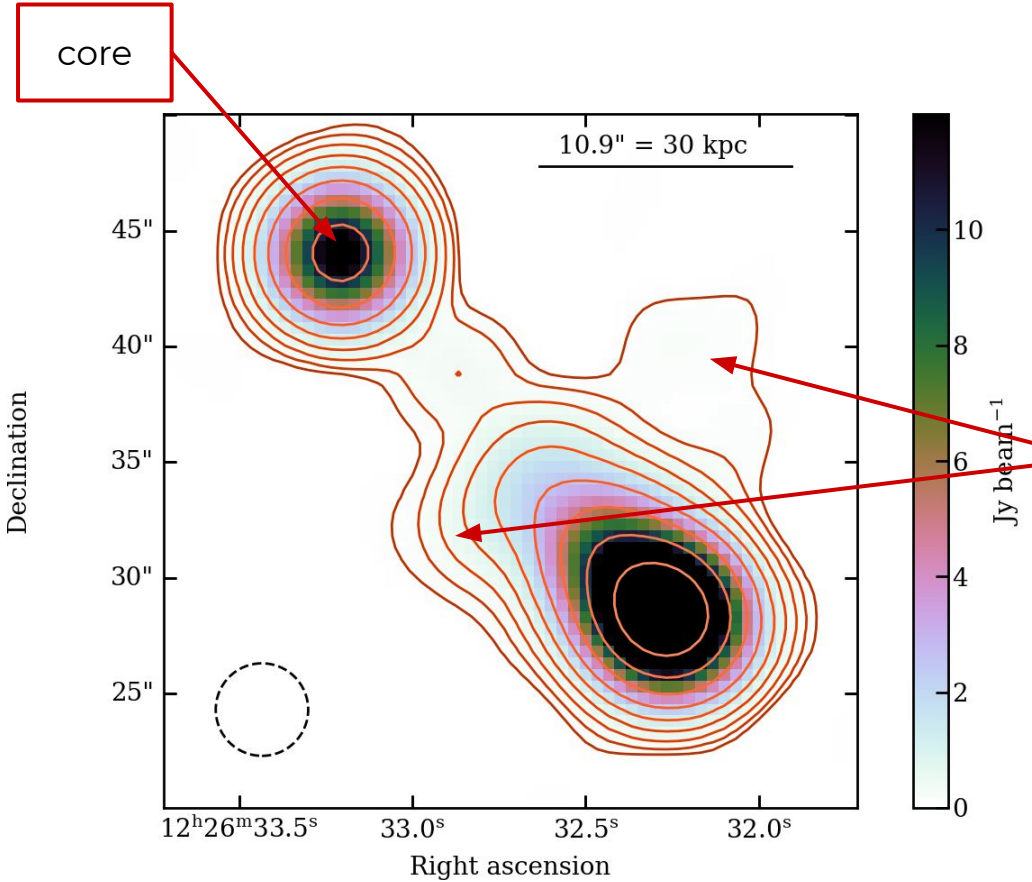
- LOFAR extends SEDs down in frequency by 1–2 orders of magnitude
- Knots A, B2, & C2 appear fainter than expected from extrapolations of GHz data
- Knot B1 not shown but upper limit can be set

Knot SEDs

Warnings:

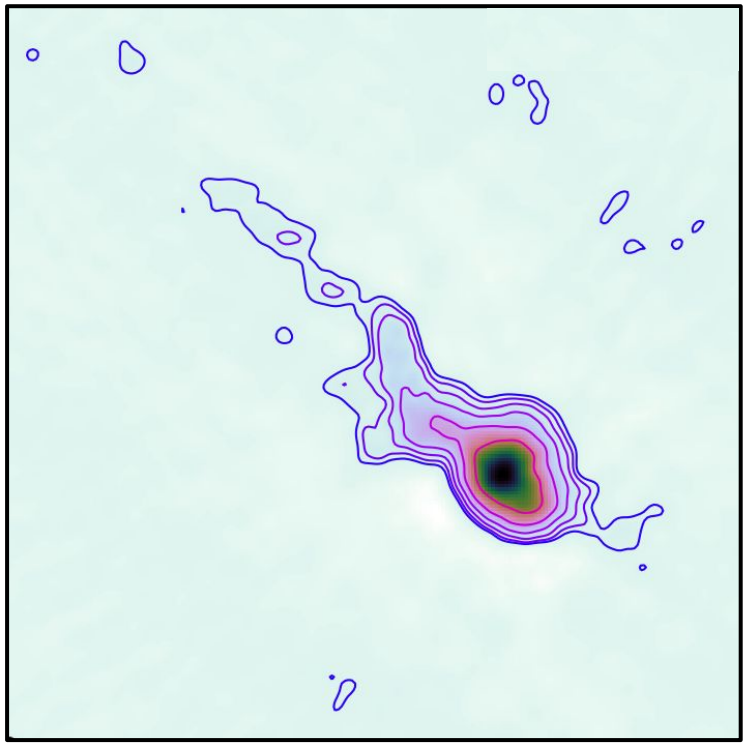
- Flux scale bootstrapped off the VLA measurements of the core so we assume the core flux is invariable on decadal timescales
- Artefacts around the core affects measured core flux
- Uncertainties need to be quantified (originating from demarcating knots & flux calibration)

Diffuse emission & jet power – VLA data

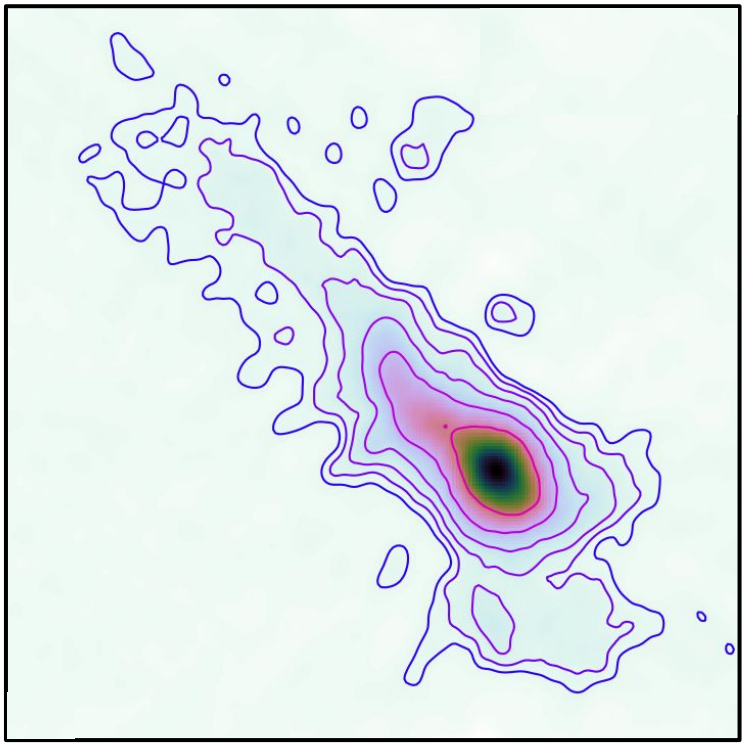


- Diffuse cocoon seen at 327 MHz with VLA
- 4” resolution image
- Data replotted from Perley & Meisenheimer 17

Diffuse emission & jet power – LOFAR data

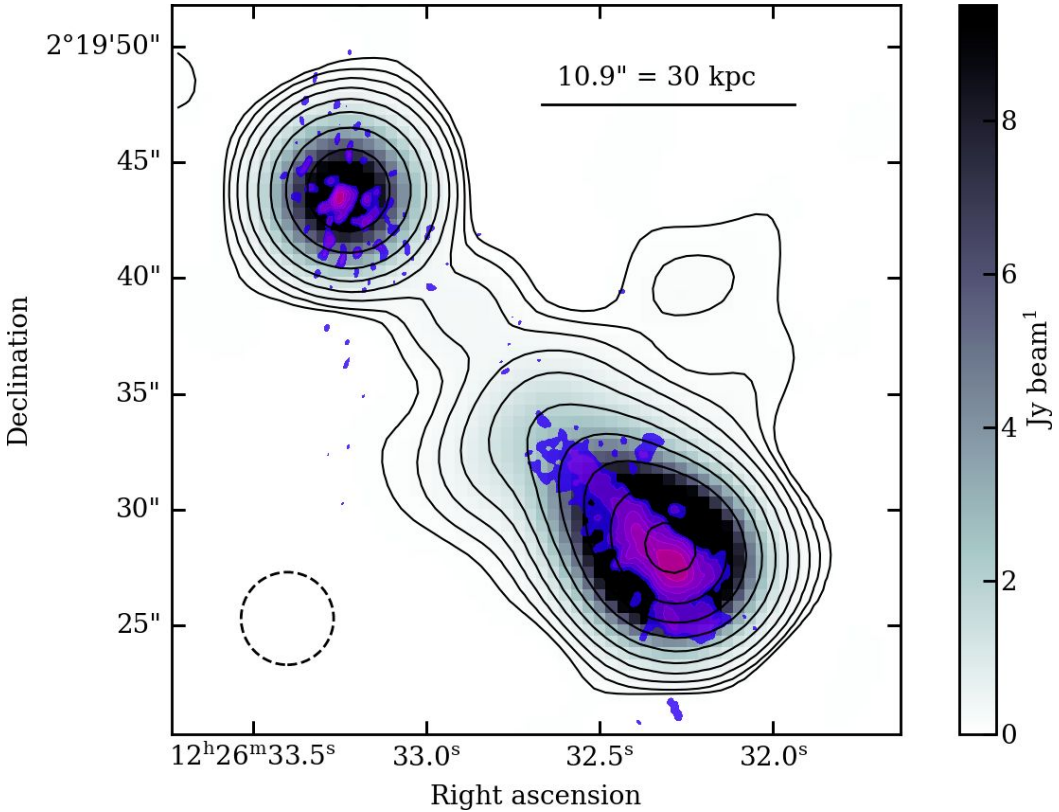


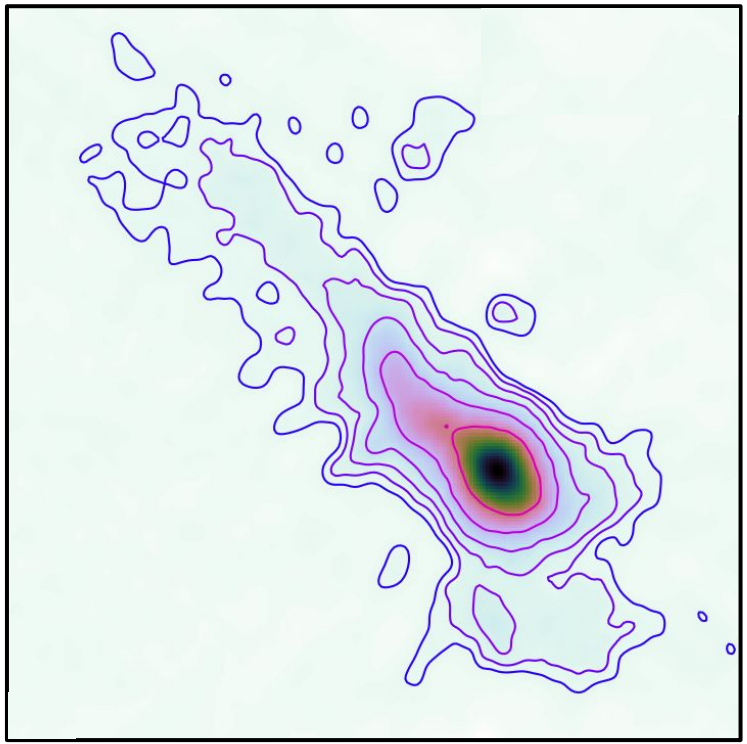
robust -2



robust -0.5

Diffuse emission & jet power – LOFAR data





robust -0.5; contours double from 80 mJy/beam

Diffuse emission & jet power

Diffuse flux density gives estimate of jet kinetic power via scaling relation, e.g. Willott+ 99, Punsly 05:

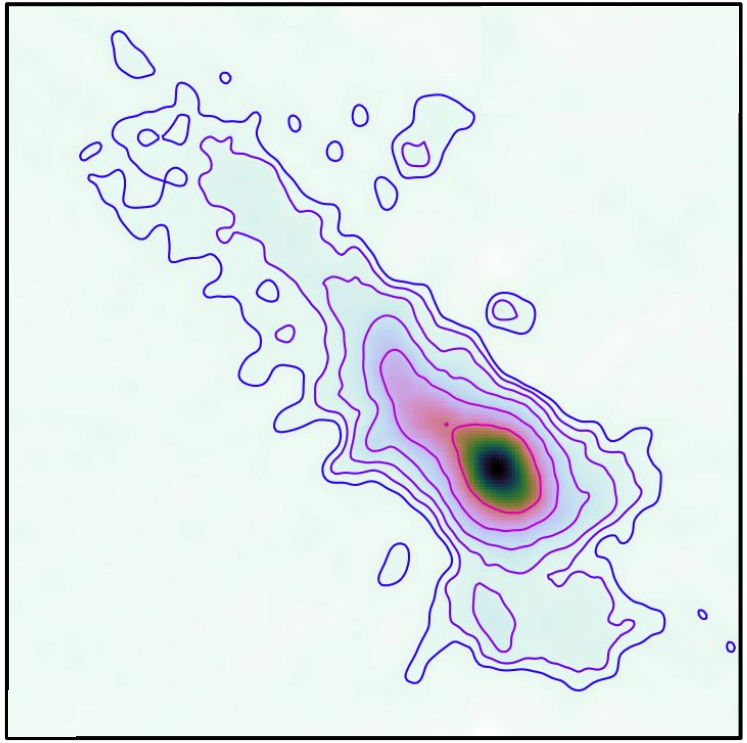
$$Q \approx \left(\frac{f}{15}\right)^{1.5} \times (1.1 \times 10^{45}) \times (X^{1+\alpha}\, Z^2\, S_{151})^{0.857}$$

$$Z \equiv 3.31 - 3.65 \times (X^4 - 0.203X^3 + 0.749X^2 + 0.444X + 0.205)^{-0.125}$$

$$X \equiv 1 + z$$

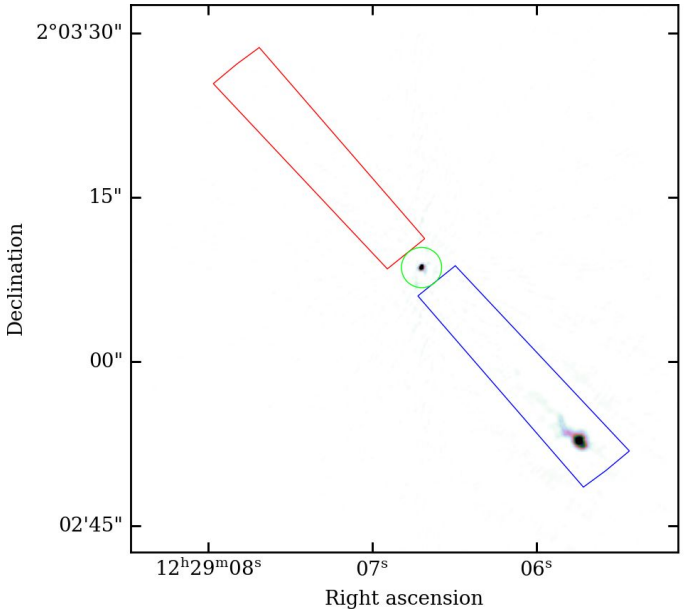
Punsly & Kharb 16 estimated the jet power as $0.7–3.7 \times 10^{44}$ erg s^{-1}

TBD...



Counterjet?

- Not detected at any wavelength or at VLBI
- Dynamic range of HBA image means the upper limit set here does not improve on previous works
- Nevertheless we use the counterjet upper limit to constrain $0.69c < v < c$ and $\Gamma > 1.4$
- Perhaps best chance to detect counterjet is with the LBA?



Next steps

- Some improvements could be made to improve final image quality:
    a. Including extra 8h?
    b. Tinkering with selfcal parameters?
    c. Rerunning analysis using initial model derived from current image?
- Spectral index map with VLA?
- Investigate new low-frequency features
- Calculate diffuse flux density
- Submit paper to MNRAS

Conclusions

- First ~0.2” resolution image <1 GHz of 3C 273
- All knots detected except for B1 as expected
- Some additional morphological features at 150 MHz that need to be examined more carefully
- Low frequency observations are ideal for calculating the diffuse flux and jet kinetic power
- These observations expand the data on the SEDs of the knots by 1–2 orders of magnitude and could be used in models to explain processes behind high-energy emission
- No sign of a counterjet but if there is one, LOFAR is the instrument best placed to find it!